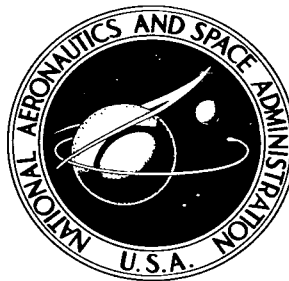


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EFFECT OF COMPOSITION, DENSITY, AND ENVIRONMENT ON THE ABLATIVE PERFORMANCE OF PHENOLIC NYLON

by Robert T. Swann, William D. Brewer, and Ronald K. Clark

Langley Research Center

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SUMMARY

Ablative materials are commonly used to protect spacecraft from the thermal environment which is encountered when entering planetary atmospheres. Materials which char when heated provide the best protection in many cases. Many char-forming materials have been formulated and tested; a mixture of phenolic resin and nylon is representative of the best performing of these ablative materials. Good thermal-protection performance has been demonstrated for a mixture of 25 percent powdered phenolic resin, 50 percent powdered nylon, and 25 percent phenolic Microballoons, molded to a density of 36 lbm/ft³ (580 kg/m³). (Percentages are based on weight.)

Experimental results are presented which show the effects of composition and density on ablative performance of phenolic and nylon mixtures. Densities of 25 to 30 lbm/ft³ (400 to 480 kg/m³) give best performance, but performance is not a strong function of either density or composition. Char spallation is observed under certain heating conditions, particularly with high nylon content and/or low density. The thermal-protection effectiveness of a castable phenolic nylon was investigated and found to be about one-half that of the molded material.

INTRODUCTION

Ablative materials are commonly used to protect spacecraft from the thermal environment encountered during atmospheric entry. Char-forming ablators provide the most effective protection for a range of entry environments. Many charring materials have been formulated and tested; phenolic nylon is representative of the best performing of these ablative materials. (See refs. 1 and 2.) Under the test conditions of references 1 and 2, it was shown that a phenolic nylon of 25 percent powdered phenolic resin, 50 percent powdered nylon, and 25 percent phenolic Microballoons (percents by weight), molded to a density of 36 lbm/ft³ (580 kg/m³), had a high thermal-protection effectiveness. This formulation was rather arbitrary; other compositions and densities, made from the same materials, might provide superior ablative performance in particular applications.

This paper presents the final results of an experimental determination of the ablative performance of phenolic nylon of various compositions and densities. The materials were evaluated in three different thermal environments. Preliminary results of this study are presented in reference 3.

An important consideration in the selection of an ablative material for application to a flight vehicle is the ease of fabrication. The elevated temperatures and pressures required to mold phenolic nylon could limit the practicability of using this material as thermal protection for large space vehicles or for vehicles with complicated shapes. It would be desirable to be able to mold the material at low pressures or perhaps even to cast the material. Therefore, the thermal-protection effectiveness of castable phenolic nylon was investigated in this program.

SYMBOLS AND ABBREVIATIONS

The units used for the quantities defined in this paper are given both in the U.S. Customary Units and in the International System of Units, SI. Factors relating the two systems are given in reference 4. Conversion factors utilized in this paper are given in the appendix.

| | |
|-----------|--|
| E | ablative effectiveness, defined as $\frac{\dot{q}t}{m}$ where t is the time required for a back-surface temperature rise of 300° F (167° K) to occur |
| \bar{E} | ablative effectiveness based on the mass of material degraded, $\frac{\dot{q}t}{\rho l_p}$ |
| f | porosity of char |
| h_e | stream enthalpy |
| k | thermal conductivity |
| l_p | thickness of material pyrolyzed |
| m | original mass of ablation material per unit area |
| p | pressure |
| \dot{q} | rate of cold-wall convective heat transfer to nonablating surface per unit area |
| r | radius of specimen |

| | |
|-----------|--|
| \dot{s} | char surface recession rate at stagnation point |
| T | absolute temperature |
| t | time |
| x | distance along surface of specimen, measured from stagnation point |
| ρ | density of original material |

Subscript:

| | |
|-----|------------|
| s | stagnation |
|-----|------------|

Abbreviations:

| | |
|-------|-------------------------------|
| Ph | phenolic resin |
| Ny | powdered nylon |
| Mic | phenolic Microballoons |
| c | cast |
| m | molded |
| m_c | molded from castable material |

MATERIALS

The ablation material used in this study is, in general, referred to as low-density phenolic nylon. This material is composed of a nylon powder, a phenolic bonding material, and phenolic Microballoons. The nylon powder used is DuPont "Zytel" 103. According to the processor, the average particle size was 80 mesh ($177 \mu\text{m}$) with a maximum size of 30 mesh ($590 \mu\text{m}$). The phenolic resin was Union Carbide "Bakelite" BRP5549 with average particle size of 200 mesh ($74 \mu\text{m}$). The phenolic Microballoons, which are cured phenolic resin in the form of minute hollow spheres, were Union Carbide

BJO-0930. The Microballoons were 270 mesh ($53\ \mu\text{m}$) average with a range from 400 mesh ($37\ \mu\text{m}$) to sizes which would not pass through a 50-mesh ($297\ \mu\text{m}$) screen.

In this investigation, the ablative composites were molded from the materials described, using various percentages of these three components. In all, eight different compositions ranging from about 18 to 44 lbm/ft³ (290 to 705 kg/m³) in density were investigated. The composition and corresponding densities are shown in table I.

The materials were mixed in 5.7 lbm (2.58 kg) batches at room temperature in a V-type blender with a capacity of 1 ft³ (0.028 m³). The blender tumbled the materials at a rate of 22 rpm (2.3 rad/s) for 1/2 hr (1.8 ks). The mixed materials were molded in an 11-in-diameter (28 cm) mold, in vacuum, at a temperature of 320° F (433° K) for a period of 2 hr. The materials were molded to a given volume to obtain the required density for each block of ablation material. Different masses of material were molded to a given volume to obtain the desired density. The initial molding pressure varied from about 100 psi to 250 psi (0.7 to 1.7 MN/m²). The materials were then cooled in the mold to room temperature. The individual test specimens were machined from the 11-in-diameter (28 cm) blocks and attached to a holder for positioning on the test apparatus.

For the cast specimens, a liquid phenolic resin was used instead of the customary powdered phenolic resin. The liquid resin was EC-251 produced by Evercoat Chemicals, Incorporated. The nylon and Microballoons were the same as those used with the powdered resin. The materials were mixed in batches of 0.22 lbm (100 g) for 1/2 hr at room temperature at 30 rpm (3.1 rad/s) in a vertical cone mixer with a capacity of 6 fl oz (178 cm³), then cast at atmospheric pressure at a temperature of 200° F (366° K), and maintained at that temperature for a period of about 18 hr. The cast specimens were 3 in. (7.6 cm) in diameter and ranged from 0.7 in. (1.8 cm) to 2.5 in. (6.4 cm) in thickness, depending on the material density. As with the powdered resin, specimens were made with various percentages of the raw materials. However, only one block density of each composition was considered and each composition had a different density. The densities of the individual test specimens varied slightly from these block densities. The compositions and corresponding densities of specimens cast from liquid resin are given in table I. Five specimens were molded from the castable resin, as indicated in table I, so that effects of processing could be separated from the effects of using a different phenolic resin.

TEST FACILITIES AND TEST CONDITIONS

The various material compositions were tested in three arc-heated jets. The test conditions are summarized in table II. The specimens were 3 in. (7.6 cm) in diameter, which was the largest size the facilities could accommodate.

The first series of tests was conducted in the 2.5-megawatt atmospheric arc jet at the Langley Research Center which is described more fully in reference 5. The tests conducted in this facility were similar to those reported in reference 1. However, the specimens were 1 in. (2.5 cm) thick rather than of such thickness that the mass was 3 lbm/ft² (15 kg/m²). Also, the stream contained 3 percent oxygen rather than 23.2 percent. This composition was used because, as shown in reference 6, the char performance in flight environments is adequately simulated in low-enthalpy test facilities only if the oxygen content of the test stream is reduced. These test conditions are summarized in table II as test condition I. Each specimen was subjected to the constant thermal environment at its front surface until a rise of 300° F (167° K) occurred at a 1/8-in-thick (0.32 cm) copper disk bonded to the back surface.

A second series of tests (test condition II, table II) was conducted in the 5-megawatt arc-powered tunnel at the Langley Research Center which is a supersonic version of the arc tunnel described in reference 7. This facility has been modified to operate at supersonic (Mach 3) velocities, but was operated in a choked condition to obtain higher stagnation pressure and heating rate. These tests usually lasted 10 sec, although in some instances the specimen was completely consumed in a shorter time. Data obtained from these tests consisted of motion pictures taken during the test and measurements of total surface recession and final char thickness made after the specimens were sectioned diametrically. No specimen temperature measurements were made in these tests.

The third series of tests (test condition III, table II) was conducted at the highest enthalpy level of the three test series. The tests were conducted in the 1-megawatt D.C. atmospheric arc jet at the Langley Research Center. The stagnation pressure was approximately 1 atm (1.013×10^5 N/m²). This facility has not yet been equipped to prevent some convective heating to the back side of the specimens. Therefore ablative performance was determined from post-test measurements of surface recession and char thickness rather than from back-surface temperature measurements.

RESULTS AND DISCUSSION

The ablative effectiveness of the material subjected to condition I was determined from the following equation:

$$E = \frac{\dot{q}t}{m} \quad (1)$$

This effectiveness is the amount of heat accommodated at the surface per unit mass of material originally available. The time t is the time at which a back-surface temperature rise of 300° F (167° K) occurs, and \dot{q} is the cold-wall convective heating rate

obtained from a calorimeter test calibration of the jet. The specimen mass per unit of area is m .

The results from materials tested at condition III were evaluated on the basis of a modified effectiveness parameter defined as follows:

$$\bar{E} = \frac{\dot{q}t}{\rho l_p} \quad (2)$$

where \bar{E} is the amount of heat accommodated per unit mass of material degraded, t is the test duration, ρ is the density of the original material, and l_p is the thickness of material pyrolyzed.

The experimental results are summarized in table I and are discussed in detail in the following sections.

Evaluation of Molded Materials

Test condition I.— Results of the tests conducted under condition I (table II) on molded specimens are shown in figure 1. For the range of compositions and densities investigated, with the exception of one specimen, ablation effectiveness ranges from about 12 000 to 16 000 Btu/lbm (27 to 37 mJ/kg). Maximum effectiveness is obtained for densities between 24 and 30 lbm/ft³ (380 to 480 kg/m³). For the range of compositions covered at a nominal density of 36 lbm/ft³ (580 kg/m³), the effect of composition on effectiveness is less than ± 10 percent of the midpoint of the data.

In general, a decrease in effectiveness with increasing density would be expected because of the lower insulating value (on a mass basis) of the higher density material. In addition, the conductivity of the uncharred material at about 200° F (366° K) appears to increase linearly with density. (See fig. 2.) No effect of composition on conductivity was observed from figure 2 which includes all compositions. The increase in the $k\rho$ product of the material accounts in part for the decrease in effectiveness as density increases beyond 30 lbm/ft³ (480 kg/m³).

The increase in effectiveness with increasing density at densities from 18 to 24 lbm/ft³ (290 to 380 kg/m³) results largely from the improvements in the physical characteristics of the char. From figure 3 it is seen that, for a given composition, char uniformity increases with increasing density over the entire density range of the investigation. With the higher densities, the materials in figure 3(b) were completely charred and flow of the test stream through the outer edge of the char resulted in the irregularities which are observed at the edges. Attention should be restricted to the stagnation area of the specimens. While no mechanical removal (spallation) of char was observed in these tests, the extreme surface roughness of the chars produced from the lowest density material of either composition could result in increased heating, or penetration, of

the test streams into the char. Thus, density has two effects on performance. First, insulating effectiveness decreases with increasing density, and this is the controlling effect at densities above 30 lbm/ft³ (480 kg/m³). Second, char uniformity improves with increasing density. This second effect is predominant at densities below 25 lbm/ft³ (400 kg/m³), at least for this environment.

For a comparison of the two lowest density materials shown in figure 3, it is seen that the material having 40 percent nylon provides the more uniform char. At higher density, the material containing 50 percent nylon provides the more uniform char. The effectiveness data for these two compositions are shown in figure 4. Detailed examination of the data shows that, in general, higher effectiveness is associated with the more uniform char.

Test condition II.- These high-pressure tests (test condition II, table II) were conducted primarily to evaluate the mechanical integrity of the char layers formed by materials of varying composition and density. The results fell in three categories. In one category, no mechanical removal of char was observed. In another, a char of appreciable thickness was built up and then periodically removed over the entire surface with a period of several seconds. In the third, the spallation was almost continuous. A brightening of small portions of the surface, indicating accumulation of char, was followed by darkening, indicating char removal. These events occurred sporadically over the entire surface.

The effect of density on weighted surface recession rate is shown in figure 5 for several compositions. Weighted surface recession rate is given by the product of the uncharred material density and the surface recession rate. Introduction of the density factor gives a parameter related to the weight of material consumed which is of strong interest in regard to payload considerations. The average rate of recession, even when weighted by the initial density as in the figure, decreases rapidly with increasing density. The recession resulted almost entirely from mechanical spallation. The large amount of scatter in the data is the result of spallation occurring for some specimens just prior to termination of the test whereas for other specimens it would probably have occurred shortly if the test had not been terminated. However, the material containing only 40 percent nylon is definitely superior to the other compositions at each density. The effect of nylon content on weighted surface recession rate is shown in figure 6. In this test condition, higher nylon content results in higher surface recession rates.

The periodic spallation which was observed in these tests consisted of complete local removal of the char down to the interface between char and uncharred material. This type of char removal might result from tensile failure at the interface as a result of internal pressure built up by gaseous products of pyrolysis as hypothesized in reference 3.

The mechanical removal of char is examined in reference 8. In that study, equations are derived and solved numerically to demonstrate that a combination of internal pressure and thermal stress can lead to periodic char removal. The ultimate tensile strength of low-density phenolic nylon is shown as a function of temperature in figure 7 (from ref. 9). At 700° F (644° K) the ultimate tensile strength is less than 50 psi (0.34 MN/m²), and at this temperature the decomposition reactions have hardly begun. Thus, it is apparent that relatively low internal pressures could result in mechanical failure of the char.

The char-layer properties affecting internal stress which are most likely to vary with material density and composition are permeability and porosity. Decreasing density and increasing nylon content would be expected to result in higher porosity and perhaps higher permeability. Higher porosity would increase the stress level, whereas higher permeability would reduce it. Thus, the effect of composition and density on porosity is probably in the direction to account for the experimental results which were obtained while the effect on permeability would tend to produce results opposite to those obtained. However, the stress is inversely proportional to 1-f, whereas the dependence of stress on permeability is less direct. In addition, there is no direct relation between porosity and permeability (ref. 10). Further information is required on the effects of composition and density on material properties. However, char removal as a result of internal pressure appears to be consistent with the data.

The development in reference 3 was based on the assumption of one-dimensional flow of the pyrolysis gases through the char layer. Because of the variable pressure distribution, the flow field will actually vary with distance from the center of the specimen. In general, the surface pressure will decrease with distance from the stagnation point. This will tend to result in lateral flow of pyrolysis products, within the char layer, away from the stagnation point. This lateral flow will reduce the pressure drop across the char layer in the stagnation area. However, in the present tests an anomaly was found in the pressure distribution. The pressure increased with distance from the stagnation point, as shown in figure 8. This pressure distribution probably results from the shock pattern which was obtained because the specimen choked the stream. This pressure distribution will result in lateral flow of pyrolysis gases toward the stagnation area. Therefore the pressure drop across the char will be greater than that estimated in reference 3.

Test condition III.- The effects of density on effectiveness of phenolic nylon in a high-enthalpy environment are shown in figure 9. As noted in equation (2), the effectiveness in this environment is based on the thickness of material degraded during the test rather than on a back-surface temperature rise. The exposure times for these tests were chosen so that some uncharred material remained after testing and the depth of the

pyrolysis could be measured. Therefore, these results are not directly comparable to those obtained at low enthalpy.

Under this test condition, the effectiveness is seen to reach the highest value at the lowest densities. Between 20 and 30 lbm/ft³ (320 and 480 kg/m³), the effectiveness is relatively insensitive to changes in density. The chars formed from low-density material in a high-enthalpy environment (fig. 10) are smoother and more uniform than those which were formed from the same material in a low-enthalpy environment (fig. 3). This accounts for the high effectiveness of the low-density material.

The effect of composition on performance was examined and the effectiveness was found to be insensitive to nylon content. The nylon content tends to be a measure of the volatile fraction. Therefore, the present results are as expected from the theoretical predictions of figure 8 in reference 6 which indicates that at intermediate enthalpies the effectiveness is insensitive to changes in volatile fraction.

Evaluation of Castable Material

The results presented in the preceding sections were obtained with molded phenolic nylon. Many of the unfavorable features of the molding process are not generic to the casting procedure, hence in the interest of ease of fabrication a castable material might be considered. The specimens which were made from castable materials were tested under Condition I (table II) and results are shown in figure 11. The effectiveness of the castable material is only about one-half that of the molded material. Additional testing and evaluation is required to explain the differences in performance of these two materials. These results indicate that further development is required if heat shields are to be cast, as in this study, from phenolic nylon.

To study further the ablative performance of materials fabricated from the liquid-resin system, specimens were molded, rather than cast, from this resin system and were tested under Condition III (table II). These results are shown in figure 12. The results are similar to those obtained with the powdered-resin system. It appears that the liquid and the powdered phenolic resin can be used interchangeably if a molding process is used.

Evaluation of Results

In general, it has been shown that when performance is predominantly determined by thermal and chemical phenomena, the effectiveness is relatively insensitive to composition (over the range covered in this study). For test condition I, peak performance is obtained with a density of about 25 lbm/ft³ (400 kg/m³). In test condition III, peak performance is obtained at the lowest densities (about 20 lbm/ft³ (320 kg/m³)). However,

in both cases, effectiveness is relatively insensitive to changes in density in the area of the peak.

Because of the relative insensitivity of the thermochemical ablative performance of the phenolic-nylon-Microballoons system to the composition and density of the material, these characteristics can be selected on some other basis. Elimination of mechanical removal of char, which occurred under test condition II (table II), is an important consideration. The fact that such removal is not understood quantitatively means that extra margins of safety must be provided in designs of heat shields which may be subject to this form of char removal. The data show that mechanical char removal increases with increasing nylon content and decreases with increasing density.

CONCLUSIONS

An experimental determination has been made of the ablative performance of phenolic nylon of various compositions and densities. The materials were evaluated in three different thermal environments. Results of the study led to the following conclusions:

1. The thermochemical ablative performance of phenolic nylon is relatively insensitive to composition and density over a considerable range of these parameters. High performance is obtained with a density of about 25 lbm/ft³ (400 kg/m³), but the effectiveness is relatively insensitive to changes in density in the area of the peak.

2. Low-density phenolic nylon is subject to mechanical spallation under high-pressure, high-heating-rate conditions. The data are consistent with the hypothesis that spallation is caused by tensile failure resulting from internal pressure. The spallation increases in severity with increasing nylon content and decreasing density.

3. Performance of specimens molded from the liquid-resin system was comparable to that of specimens fabricated from the powdered-resin system, indicating that the two systems can be used interchangeably. However, the thermal-protection effectiveness of the cast material was only one-half that of the molded material. Thus further development of the casting process is necessary to achieve an effective ablation system with much more ease of fabrication.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., December 2, 1966,
124-08-03-16-23.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (ref. 1) (SI) was adopted in 1960 by the Eleventh General Conference on Weights and Measures held in Paris, France. Conversion factors required for units used herein are given in the following table:

| Physical quantity | U.S. Customary Unit | Conversion factor (*) | SI Unit |
|---------------------------------|--------------------------|--------------------------|----------------------|
| Angular velocity | rpm | 10.48×10^{-2} | rad/s |
| Density | lbm/ft ³ | 16.02 | kg/m ³ |
| Effectiveness | Btu/lbm | 2.32×10^3 | J/kg |
| Enthalpy | Btu/lbm | 2.32×10^3 | J/kg |
| Heat-transfer rate | Btu/ft ² -sec | 1.13×10^4 | W/m ² |
| Length | ft | 0.305 | m |
| | in. | 2.54×10^{-2} | m |
| Mass | lbm | 0.454 | kg |
| Mass flow rate | lbm/sec | 0.454 | kg/s |
| Mass per unit area | lbm/ft ² | 4.88 | kg/m ² |
| Pressure | atm | 1.013×10^5 | N/m ² |
| | lbf/ft ² | 47.88 | N/m ² |
| Surface recession rate | ft/sec | 0.305 | m/s |
| Temperature | °F | $5/9 (°F + 460)$ | °K |
| Temperature rise | °F | 0.556 | °K |
| Thermal conductivity | Btu/ft-sec-°R | 6.23×10^3 | W/m-°K |
| Volume | ft ³ | 2.83×10^{-2} | m ³ |
| | fl oz | 2.96×10^{-5} | m ³ |
| Weighted surface recession rate | lbm/ft ² -sec | 4.88 | kg/m ² -s |

*Multiply value given in U.S. Customary Unit by conversion factor to obtain equivalent value in SI Unit.

Prefixes to indicate multiples of units are as follows:

| Prefix | Multiple |
|-----------|------------------|
| micro (μ) | 10 ⁻⁶ |
| centi (c) | 10 ⁻² |
| kilo (k) | 10 ³ |
| mega (M) | 10 ⁶ |

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TABLE I.- SUMMARY OF MATERIALS AND TEST RESULTS

(a) Test condition I

| Specimen | Composition, percent by weight | | | Type of material | Specimen density | | Cold-wall heating rate | | Time for back- surface tempera- ture to increase 300° F (167° K), s | Effectiveness, E = qt/m | |
|----------|--------------------------------------|----|-----|------------------|------------------------|----------------------|-----------------------------|----------------------|---|----------------------------|----------|
| | Ph | Ny | Mic | | lbm ft ³ | kg m ³ | Btu ft ² -sec | MW m ² | | Btu lbm | MJ kg |
| 1 | 25 | 50 | 25 | m | 20.9 | 335 | 109 | 1.23 | 207 | 12 960 | 30.1 |
| 2 | ↓ | ↓ | ↓ | ↓ | 21.2 | 340 | 108 | 1.22 | 213 | 13 020 | 30.2 |
| 3 | ↓ | ↓ | ↓ | ↓ | 24.5 | 392 | 114 | 1.29 | 259 | 14 460 | 33.6 |
| 4 | ↓ | ↓ | ↓ | ↓ | 25.1 | 402 | 114 | 1.29 | 264 | 14 390 | 33.4 |
| 5 | ↓ | ↓ | ↓ | ↓ | 30.3 | 485 | 117 | 1.32 | 329 | 15 250 | 35.4 |
| 6 | ↓ | ↓ | ↓ | ↓ | 32.1 | 514 | 112 | 1.27 | 349 | 14 610 | 33.9 |
| 7 | ↓ | ↓ | ↓ | ↓ | 39.7 | 636 | 110 | 1.24 | 400 | 13 300 | 30.9 |
| 8 | ↓ | ↓ | ↓ | ↓ | 44.3 | 710 | 118 | 1.33 | 275 | 8 790 | 20.4 |
| 9 | ↓ | ↓ | ↓ | c | 20.8 | 333 | 112 | 1.26 | 227 | 9 170 | 21.3 |
| 10 | ↓ | ↓ | ↓ | c | 36.6 | 586 | 116 | 1.31 | 224 | 5 330 | 12.4 |
| 11 | ↓ | ↓ | ↓ | m _c | 29.9 | 479 | 121 | 1.37 | 274 | 13 310 | 30.9 |
| 12 | ↓ | ↓ | ↓ | m _c | 32.5 | 521 | 125 | 1.41 | 324 | 14 950 | 34.7 |
| 13 | 15 | 50 | 35 | m | 18.7 | 300 | 110 | 1.24 | 188 | 13 270 | 30.8 |
| 14 | ↓ | ↓ | ↓ | ↓ | 23.5 | 376 | 111 | 1.25 | 277 | 15 700 | 36.4 |
| 15 | ↓ | ↓ | ↓ | ↓ | 24.3 | 389 | 118 | 1.33 | 262 | 15 270 | 35.4 |
| 16 | ↓ | ↓ | ↓ | ↓ | 31.1 | 498 | 105 | 1.19 | 346 | 14 020 | 32.5 |
| 17 | ↓ | ↓ | ↓ | ↓ | 31.3 | 501 | 113 | 1.28 | 338 | 14 640 | 34.0 |
| 18 | ↓ | ↓ | ↓ | ↓ | 35.3 | 566 | 115 | 1.30 | 377 | 14 740 | 34.2 |
| 19 | ↓ | ↓ | ↓ | ↓ | 36.7 | 588 | 115 | 1.30 | 377 | 14 330 | 32.3 |
| 20 | ↓ | ↓ | ↓ | ↓ | 38.6 | 618 | 109 | 1.23 | 354 | 12 000 | 27.8 |
| 21 | ↓ | ↓ | ↓ | ↓ | 39.2 | 628 | 112 | 1.27 | 392 | 13 440 | 31.2 |
| 22 | ↓ | ↓ | ↓ | c | 35.8 | 574 | 116 | 1.31 | 231 | 4 990 | 11.6 |
| 23 | 25 | 40 | 35 | m | 18.7 | 300 | 107 | 1.21 | 191 | 13 120 | 30.4 |
| 24 | ↓ | ↓ | ↓ | ↓ | 23.5 | 376 | 111 | 1.25 | 247 | 14 000 | 32.5 |
| 25 | ↓ | ↓ | ↓ | ↓ | 31.5 | 505 | 108 | 1.22 | 328 | 13 500 | 31.3 |
| 26 | ↓ | ↓ | ↓ | ↓ | 33.9 | 543 | 115 | 1.30 | 341 | 13 880 | 32.2 |
| 27 | ↓ | ↓ | ↓ | ↓ | 37.8 | 606 | 106 | 1.20 | 343 | 11 540 | 26.8 |
| 28 | ↓ | ↓ | ↓ | c | 14.2 | 227 | 124 | 1.40 | 166 | 6 960 | 16.2 |
| 29 | ↓ | ↓ | ↓ | c | 15.6 | 250 | 124 | 1.40 | 200 | 8 290 | 19.2 |
| 30 | 35 | 40 | 25 | m | 27.9 | 447 | 122 | 1.38 | 304 | 15 950 | 37.0 |
| 31 | ↓ | ↓ | ↓ | m | 28.2 | 452 | 120 | 1.36 | 295 | 15 060 | 34.9 |
| 32 | ↓ | ↓ | ↓ | c | 17.2 | 276 | 118 | 1.33 | 204 | 7 800 | 18.1 |
| 33 | ↓ | ↓ | ↓ | c | 18.1 | 290 | 128 | 1.45 | 204 | 8 660 | 20.1 |
| 34 | 35 | 30 | 35 | m | 24.1 | 386 | 123 | 1.39 | 247 | 15 680 | 36.4 |
| 35 | 35 | 30 | 35 | m | 30.3 | 485 | 124 | 1.40 | 256 | 12 570 | 29.2 |
| 36 | 35 | 50 | 15 | m | 35.4 | 567 | 111 | 1.25 | 345 | 12 980 | 30.1 |
| 37 | ↓ | ↓ | ↓ | m | 37.3 | 598 | 121 | 1.37 | 351 | 13 660 | 31.7 |
| 38 | ↓ | ↓ | ↓ | c | 36.2 | 580 | 113 | 1.28 | 213 | 6 140 | 14.2 |
| 39 | 25 | 60 | 15 | m | 36.2 | 580 | 115 | 1.30 | 343 | 13 080 | 30.3 |
| 40 | ↓ | ↓ | ↓ | m | 36.5 | 585 | 116 | 1.31 | 376 | 14 340 | 33.3 |
| 41 | ↓ | ↓ | ↓ | c | 27.8 | 445 | 108 | 1.22 | 167 | 7 080 | 16.4 |
| 42 | ↓ | ↓ | ↓ | c | 28.7 | 460 | 108 | 1.22 | 219 | 9 020 | 20.9 |
| 43 | 15 | 60 | 25 | m | 34.6 | 554 | 122 | 1.38 | 326 | 13 790 | 32.0 |
| 44 | 15 | 60 | 25 | m | 35.5 | 569 | 112 | 1.27 | 362 | 13 700 | 31.8 |

TABLE I.- SUMMARY OF MATERIALS AND TEST RESULTS - Continued

(b) Test condition II

| Specimen | Composition, percent by weight | | | Type of material | Specimen density | | Surface recession | | Test time, s | Surface recession rate, \dot{s} | | Weighted surface recession rate, $\rho\dot{s}$ | |
|----------|--------------------------------------|----|-----|------------------|----------------------------------|--------------------------------|-----------------------|------|--------------------|---|------------------------------|--|---|
| | Ph | Ny | Mic | | $\frac{\text{lbm}}{\text{ft}^3}$ | $\frac{\text{kg}}{\text{m}^3}$ | ft | cm | | ft/sec | $\frac{\text{cm}}{\text{s}}$ | $\frac{\text{lbm}}{\text{ft}^2\text{-sec}}$ | $\frac{\text{kg}}{\text{m}^2\text{-s}}$ |
| 45 | 25 | 50 | 25 | m | 24.3 | 389 | 2.87×10^{-2} | 0.88 | 10 | 2.87×10^{-3} | 0.088 | 0.070 | 0.338 |
| 46 | ↓ | ↓ | ↓ | ↓ | 30.5 | 489 | 1.15 | .35 | ↓ | 1.15 | .035 | .035 | .169 |
| 47 | ↓ | ↓ | ↓ | ↓ | 30.5 | 489 | 1.25 | .38 | ↓ | 1.25 | .038 | .038 | .183 |
| 48 | ↓ | ↓ | ↓ | ↓ | 34.8 | 557 | .33 | .10 | ↓ | .33 | .010 | .011 | .053 |
| 49 | ↓ | ↓ | ↓ | ↓ | 42.5 | 681 | .29 | .09 | ↓ | .29 | .009 | .012 | .058 |
| 50 | ↓ | ↓ | ↓ | ↓ | 42.5 | 681 | .30 | .09 | ↓ | .30 | .009 | .013 | .063 |
| 51 | 15 | 50 | 35 | m | 18.6 | 298 | 6.79×10^{-2} | 2.07 | 10 | 6.79×10^{-3} | 0.207 | 0.126 | 0.610 |
| 52 | ↓ | ↓ | ↓ | ↓ | 24.9 | 399 | 2.15 | .66 | ↓ | 2.15 | .066 | .054 | .261 |
| 53 | ↓ | ↓ | ↓ | ↓ | 24.9 | 399 | 1.85 | .56 | ↓ | 1.85 | .056 | .046 | .222 |
| 54 | ↓ | ↓ | ↓ | ↓ | 36.0 | 577 | .94 | .29 | ↓ | .94 | .029 | .034 | .165 |
| 55 | ↓ | ↓ | ↓ | ↓ | 42.1 | 674 | .05 | .02 | ↓ | .05 | .002 | .002 | .010 |
| 56 | 25 | 40 | 35 | m | 18.7 | 300 | 1.98×10^{-2} | 0.60 | 10 | 1.98×10^{-3} | 0.060 | 0.037 | 0.179 |
| 57 | ↓ | ↓ | ↓ | ↓ | 18.7 | 300 | 2.65 | .81 | ↓ | 2.65 | .081 | .050 | .242 |
| 58 | ↓ | ↓ | ↓ | ↓ | 23.4 | 375 | 1.26 | .38 | ↓ | 1.26 | .038 | .029 | .140 |
| 59 | ↓ | ↓ | ↓ | ↓ | 23.4 | 375 | .91 | .28 | ↓ | .91 | .028 | .021 | .101 |
| 60 | ↓ | ↓ | ↓ | ↓ | 30.3 | 485 | .21 | .06 | ↓ | .20 | .006 | .006 | .029 |
| 61 | ↓ | ↓ | ↓ | ↓ | 30.3 | 485 | .05 | .02 | ↓ | .05 | .002 | .002 | .010 |
| 62 | ↓ | ↓ | ↓ | ↓ | 36.0 | 577 | 0 | 0 | ↓ | 0 | 0 | 0 | 0 |
| 63 | ↓ | ↓ | ↓ | ↓ | 42.6 | 682 | 0 | 0 | ↓ | 0 | 0 | 0 | 0 |
| 64 | 35 | 40 | 25 | m | 30.5 | 489 | 0.25×10^{-2} | 0.08 | 10 | 0.25×10^{-3} | 0.008 | 0.008 | 0.039 |
| 65 | 35 | 40 | 25 | m | 36.7 | 588 | .03 | .01 | 10 | .03 | .001 | .001 | .048 |
| 66 | 35 | 30 | 35 | m | 24.4 | 391 | 0.34×10^{-2} | 0.10 | 10 | 0.34 | 0.010 | 0.008 | 0.039 |
| 67 | 35 | 30 | 35 | m | 30.0 | 481 | .29 | .09 | 10 | .29 | .009 | .009 | .044 |
| 68 | 35 | 50 | 15 | m | 36.3 | 582 | 0.40×10^{-2} | 0.12 | 10 | 0.40×10^{-3} | 0.012 | 0.015 | 0.073 |
| 69 | 25 | 60 | 15 | m | 36.0 | 577 | 1.27×10^{-2} | 0.39 | 10 | 1.27×10^{-3} | 0.039 | 0.046 | 0.222 |
| 70 | 15 | 60 | 25 | m | 35.8 | 574 | 1.03×10^{-2} | 0.31 | 10 | 1.03×10^{-3} | 0.031 | 0.037 | 0.179 |

TABLE I.- SUMMARY OF MATERIALS AND TEST RESULTS - Concluded

(c) Test condition III

| Specimen | Composition, percent by weight | | | Type of material | Specimen density | | Interface recession, l_p | | Test time, s | Effectiveness, $\bar{E} = \dot{q}t/\rho l_p$ | |
|----------|-----------------------------------|----|-----|------------------|----------------------------------|--------------------------------|----------------------------------|------|--------------------|---|-------------------------------|
| | Ph | Ny | Mic | | $\frac{\text{lbm}}{\text{ft}^3}$ | $\frac{\text{kg}}{\text{m}^3}$ | ft | cm | | $\frac{\text{Btu}}{\text{lbm}}$ | $\frac{\text{MJ}}{\text{kg}}$ |
| 71 | 25 | 50 | 25 | m | 24.2 | 388 | 4.41×10^{-2} | 1.35 | 30 | 14 060 | 32.6 |
| 72 | ↓ | ↓ | ↓ | ↓ | 30.3 | 485 | 3.42 | 1.04 | 30 | 14 480 | 33.6 |
| 73 | ↓ | ↓ | ↓ | ↓ | 39.2 | 628 | 4.41 | 1.35 | 60 | 17 400 | 40.4 |
| 74 | ↓ | ↓ | ↓ | ↓ | 39.2 | 628 | 3.66 | 1.12 | 30 | 10 460 | 24.3 |
| 75 | ↓ | ↓ | ↓ | m_c | 30.0 | 481 | 3.50 | 1.07 | 30 | 14 290 | 33.1 |
| 76 | ↓ | ↓ | ↓ | m_c | 34.9 | 559 | 2.92 | .89 | 30 | 14 720 | 34.1 |
| 77 | 15 | 50 | 35 | m | 18.9 | 303 | 5.25×10^{-2} | 1.60 | 30 | 15 120 | 35.1 |
| 78 | ↓ | ↓ | ↓ | ↓ | 23.1 | 370 | 4.00 | 1.22 | 30 | 16 230 | 37.6 |
| 79 | ↓ | ↓ | ↓ | ↓ | 30.5 | 489 | 3.08 | .94 | 30 | 15 970 | 37.1 |
| 80 | ↓ | ↓ | ↓ | ↓ | 34.3 | 549 | 4.75 | 1.45 | 60 | 18 410 | 42.7 |
| 81 | ↓ | ↓ | ↓ | ↓ | 44.1 | 706 | 2.66 | .81 | 30 | 12 790 | 29.7 |
| 82 | 25 | 40 | 35 | m | 19.2 | 308 | 4.58×10^{-2} | 1.40 | 30 | 17 060 | 39.6 |
| 83 | ↓ | ↓ | ↓ | ↓ | 23.6 | 378 | 3.92 | 1.20 | 30 | 16 210 | 37.6 |
| 84 | ↓ | ↓ | ↓ | ↓ | 24.1 | 386 | 4.41 | 1.35 | 30 | 14 110 | 32.7 |
| 85 | ↓ | ↓ | ↓ | ↓ | 27.9 | 447 | 3.33 | 1.02 | 30 | 16 150 | 37.5 |
| 86 | ↓ | ↓ | ↓ | ↓ | 37.5 | 601 | 2.92 | .89 | 30 | 13 700 | 31.8 |
| 87 | ↓ | ↓ | ↓ | m_c | 35.2 | 564 | 3.33 | 1.02 | 30 | 12 800 | 29.7 |
| 88 | 35 | 40 | 25 | m | 29.2 | 468 | 3.50×10^{-2} | 1.07 | 30 | 14 680 | 34.1 |
| 89 | 35 | 30 | 35 | m | 23.3 | 373 | 4.92×10^{-2} | 1.50 | 30 | 13 090 | 30.3 |
| 90 | ↓ | ↓ | ↓ | ↓ | 23.8 | 381 | 4.92 | 1.50 | 30 | 13 090 | 30.3 |
| 91 | ↓ | ↓ | ↓ | ↓ | 28.1 | 450 | 3.50 | 1.07 | 30 | 15 250 | 35.4 |
| 92 | ↓ | ↓ | ↓ | ↓ | 30.8 | 493 | 3.16 | .96 | 30 | 15 410 | 35.7 |
| 93 | 35 | 50 | 15 | m | 35.5 | 569 | 5.08×10^{-2} | 1.55 | 60 | 16 640 | 38.6 |
| 94 | 25 | 60 | 15 | m | 36.0 | 577 | 5.00×10^{-2} | 1.53 | 60 | 16 670 | 38.7 |
| 95 | 15 | 60 | 25 | m | 34.7 | 556 | 5.08×10^{-2} | 1.55 | 60 | 17 020 | 39.5 |

TABLE II.- SUMMARY OF TEST CONDITIONS

| Test condition | \dot{q} | | h_e | | p_s | | Stream composition | Mass flow rate | | Nozzle diameter | | Power input, kW | Termination of tests |
|----------------|---|--------------------------------|---------------------------------|-------------------------------|-------|--------------------------------|---|---------------------------------|------------------------------|-----------------|------|-----------------|---|
| | $\frac{\text{Btu}}{\text{ft}^2\text{-sec}}$ | $\frac{\text{MW}}{\text{m}^2}$ | $\frac{\text{Btu}}{\text{lbm}}$ | $\frac{\text{MJ}}{\text{kg}}$ | atm | $\frac{\text{MN}}{\text{m}^2}$ | | $\frac{\text{lbm}}{\text{sec}}$ | $\frac{\text{kg}}{\text{s}}$ | in. | cm | | |
| I | ≈ 110 | ≈ 1.24 | 2 300 | 5.34 | 1.0 | 0.10 | 97% N ₂ 3% O ₂ | 0.35 | 0.16 | 4.0 | 10.2 | 2200 | When back-surface temperature increased 300° F (167° K) |
| II | 350 | 3.96 | 2 300 | 5.34 | 1.8 | 0.18 | 97% N ₂ 3% O ₂ | 0.70 | 0.32 | 4.0 | 10.2 | 3700 | 10 sec |
| III | 500 | 5.65 | 12 500 | 29.0 | 1.0 | 0.10 | Air | 0.035 | 0.016 | 3.0 | 7.6 | 725 | 30 or 60 sec |

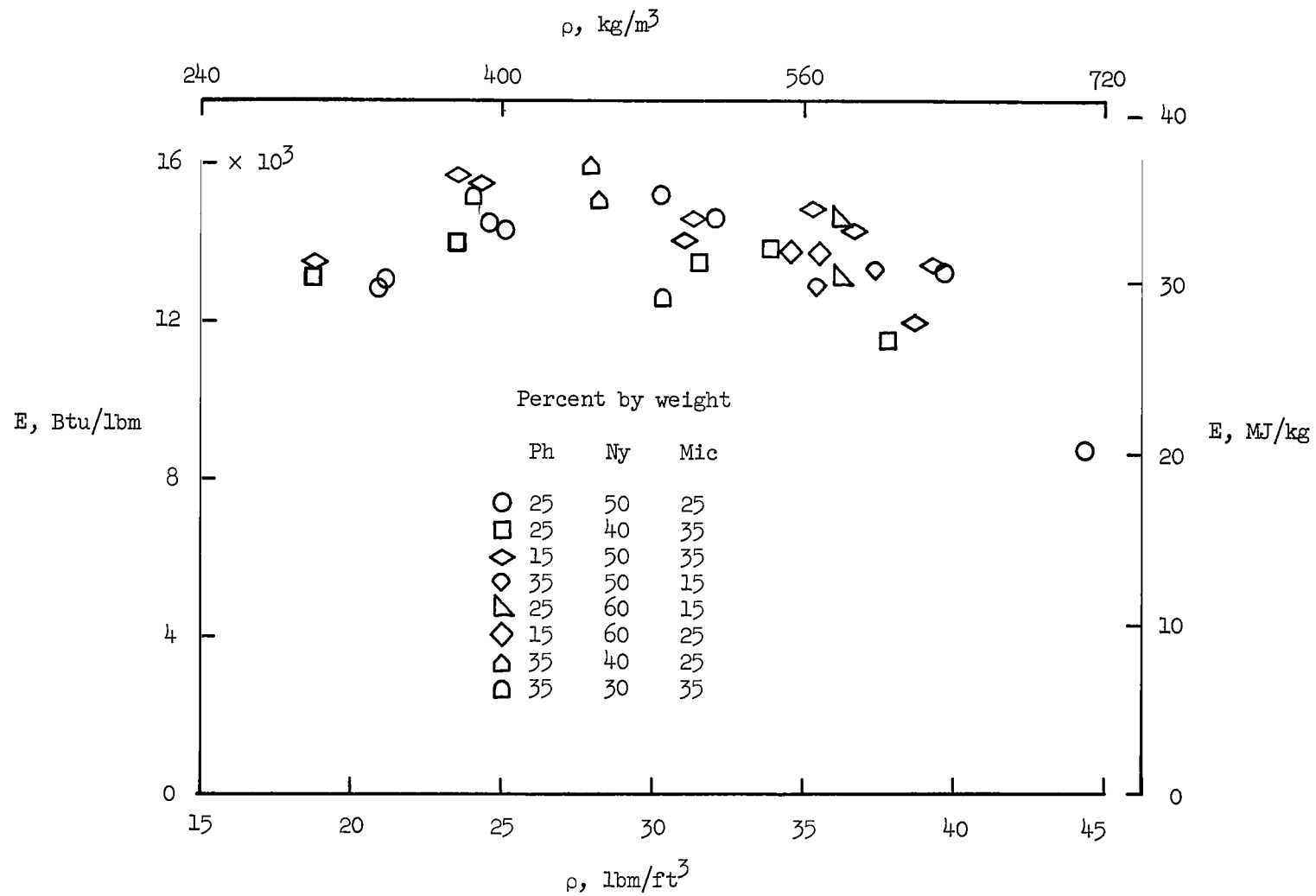


Figure 1.- Effect of density on effectiveness of phenolic nylon at test condition I.

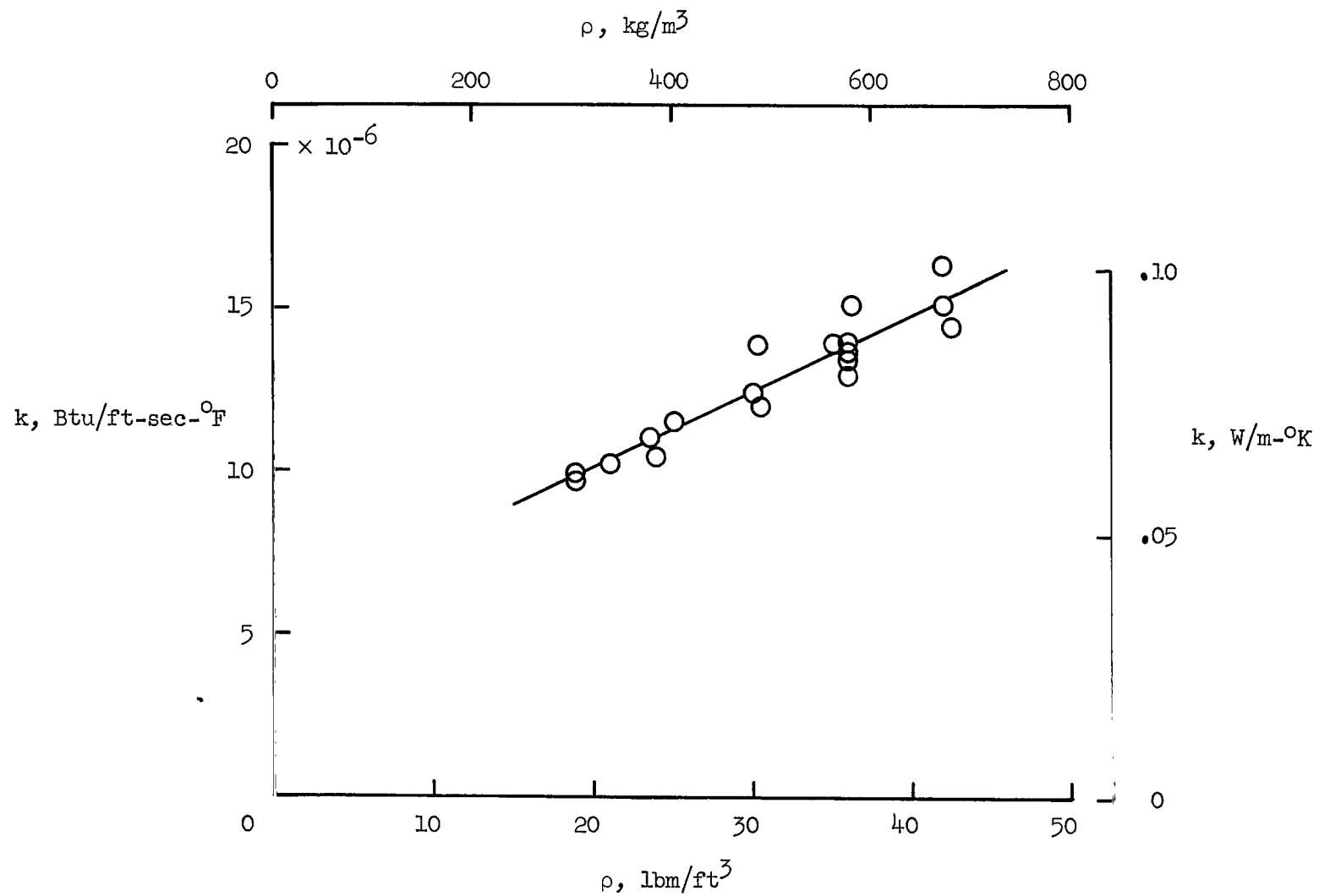
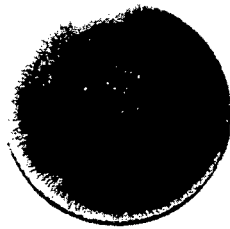


Figure 2.- Effect of density on thermal conductivity of uncharred phenolic nylon at approximately 200° F (366° K). All compositions included.



$$\rho = 20.9 \text{ lbm/ft}^3 \\ (334 \text{ kg/m}^3)$$

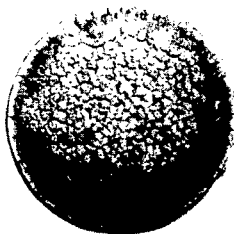


$$\rho = 32.7 \text{ lbm/ft}^3 \\ (523 \text{ kg/m}^3)$$



$$\rho = 39.7 \text{ lbm/ft}^3 \\ (635 \text{ kg/m}^3)$$

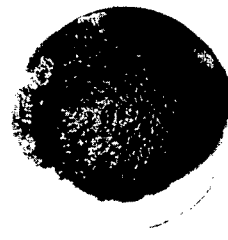
(a) 25 percent phenolic, 50 percent nylon, 25 percent Microballoons.



$$\rho = 18.7 \text{ lbm/ft}^3 \\ (299 \text{ kg/m}^3)$$



$$\rho = 33.9 \text{ lbm/ft}^3 \\ (542 \text{ kg/m}^3)$$



$$\rho = 37.8 \text{ lbm/ft}^3 \\ (605 \text{ kg/m}^3)$$

(b) 25 percent phenolic, 40 percent nylon, 35 percent Microballoons.

Figure 3.- Surface condition after testing in condition I.

L-66-7632

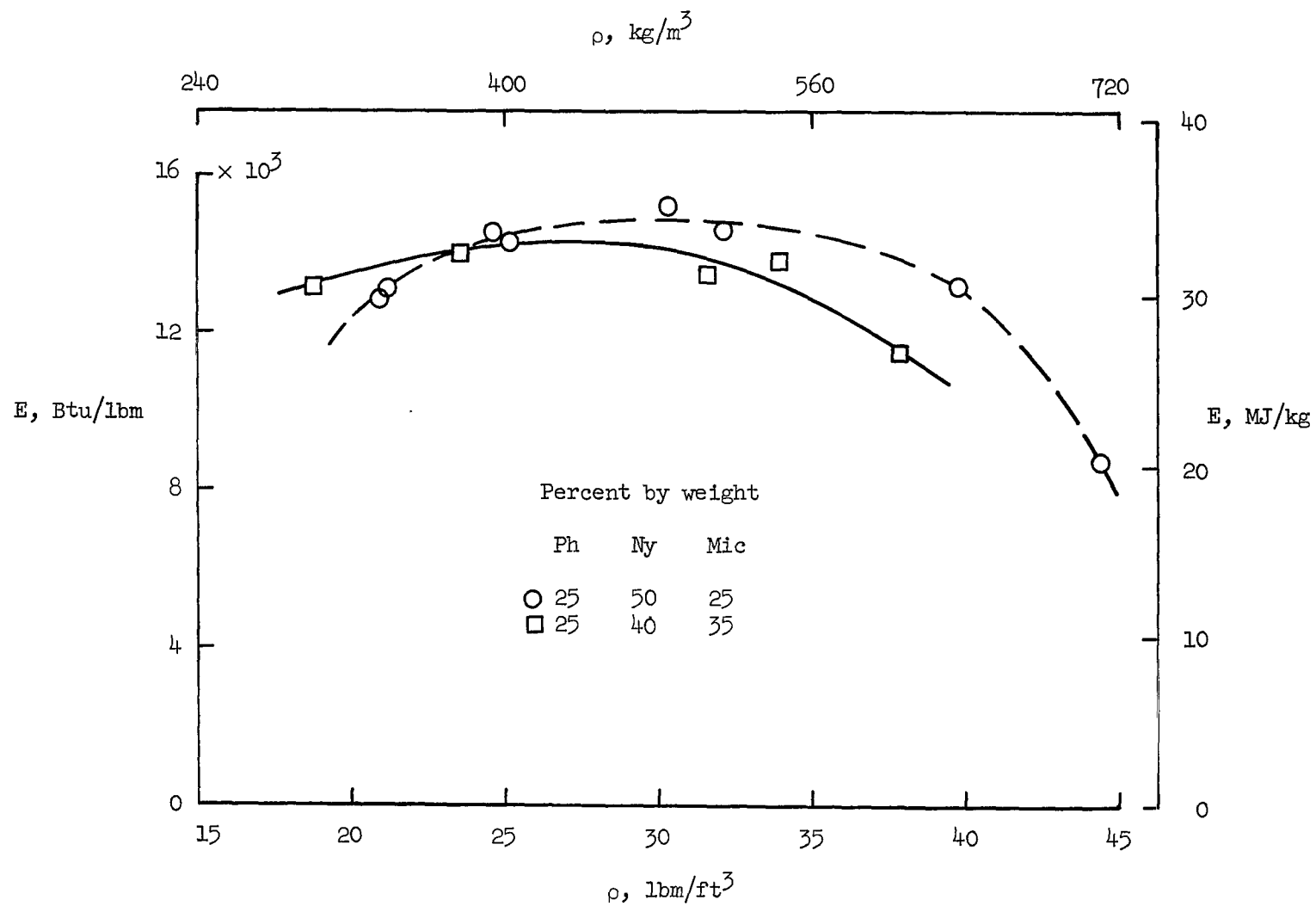


Figure 4.- Combined effect of density and composition on effectiveness at test condition 1.

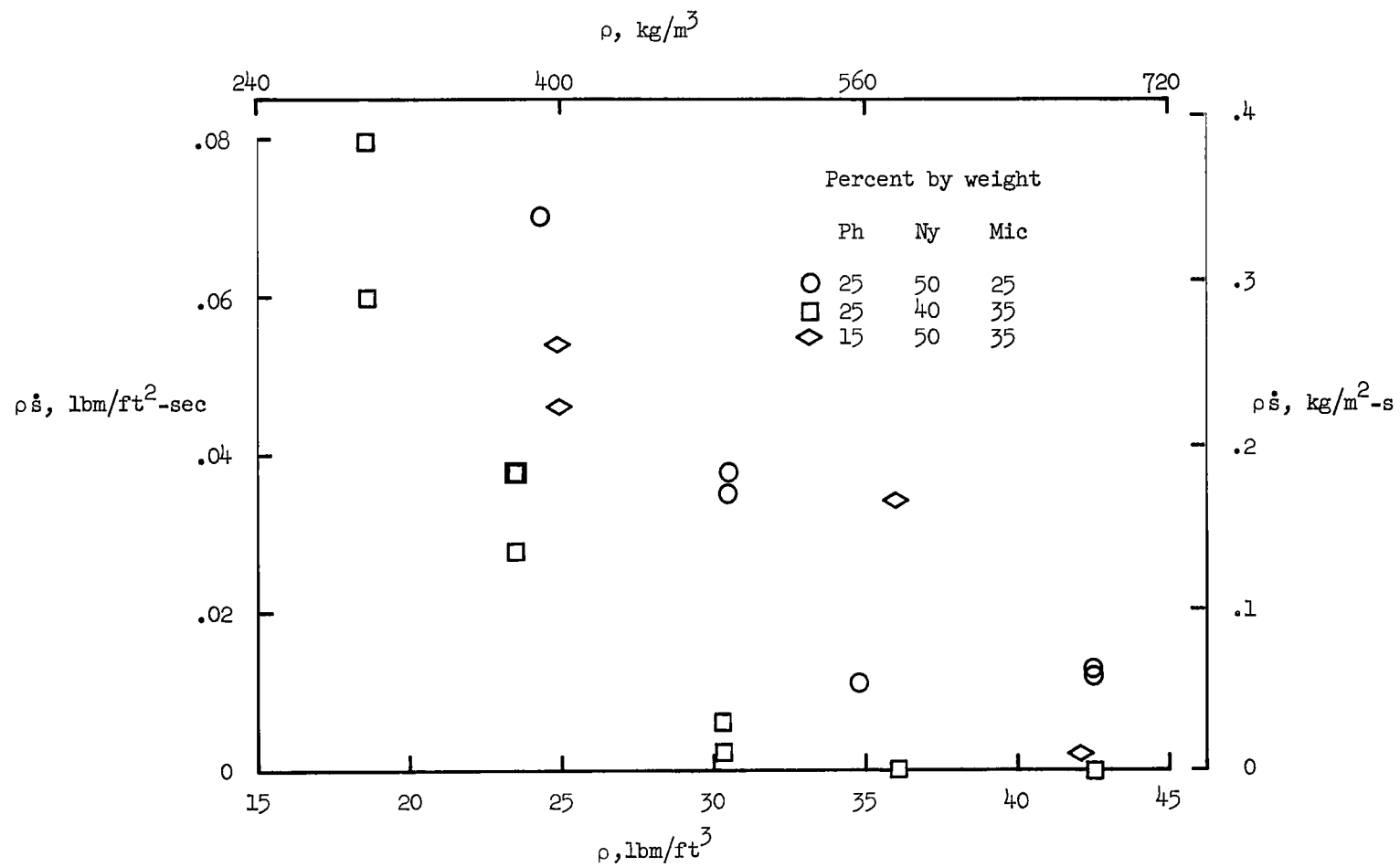


Figure 5.- Combined effect of density and composition on weighted surface recession rate at test condition 11.

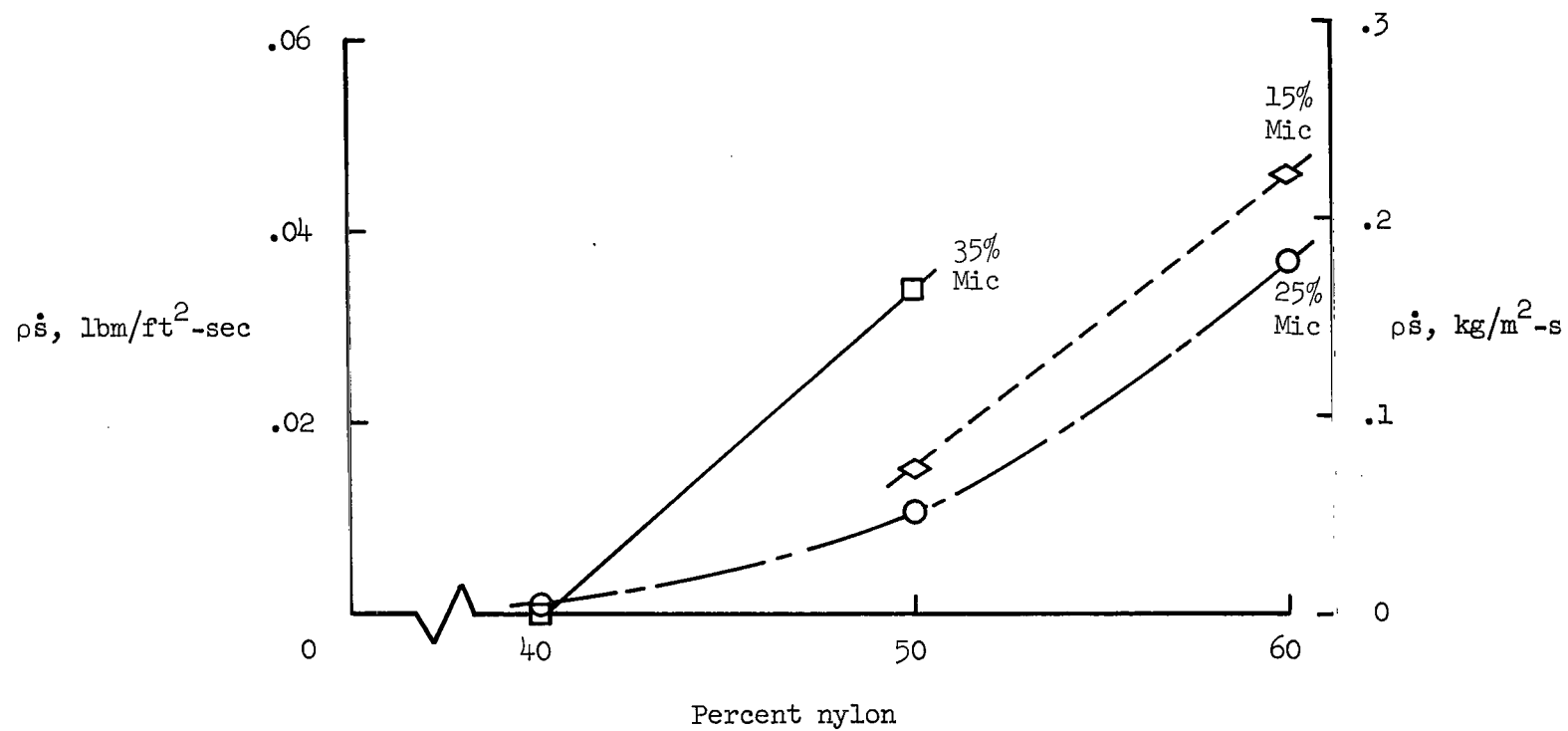


Figure 6.- Effect of nylon content on weighted surface recession rate at test condition II.
 Uncharred material density $\approx 36 \text{ lbm/ft}^3$ (577 kg/m^3).

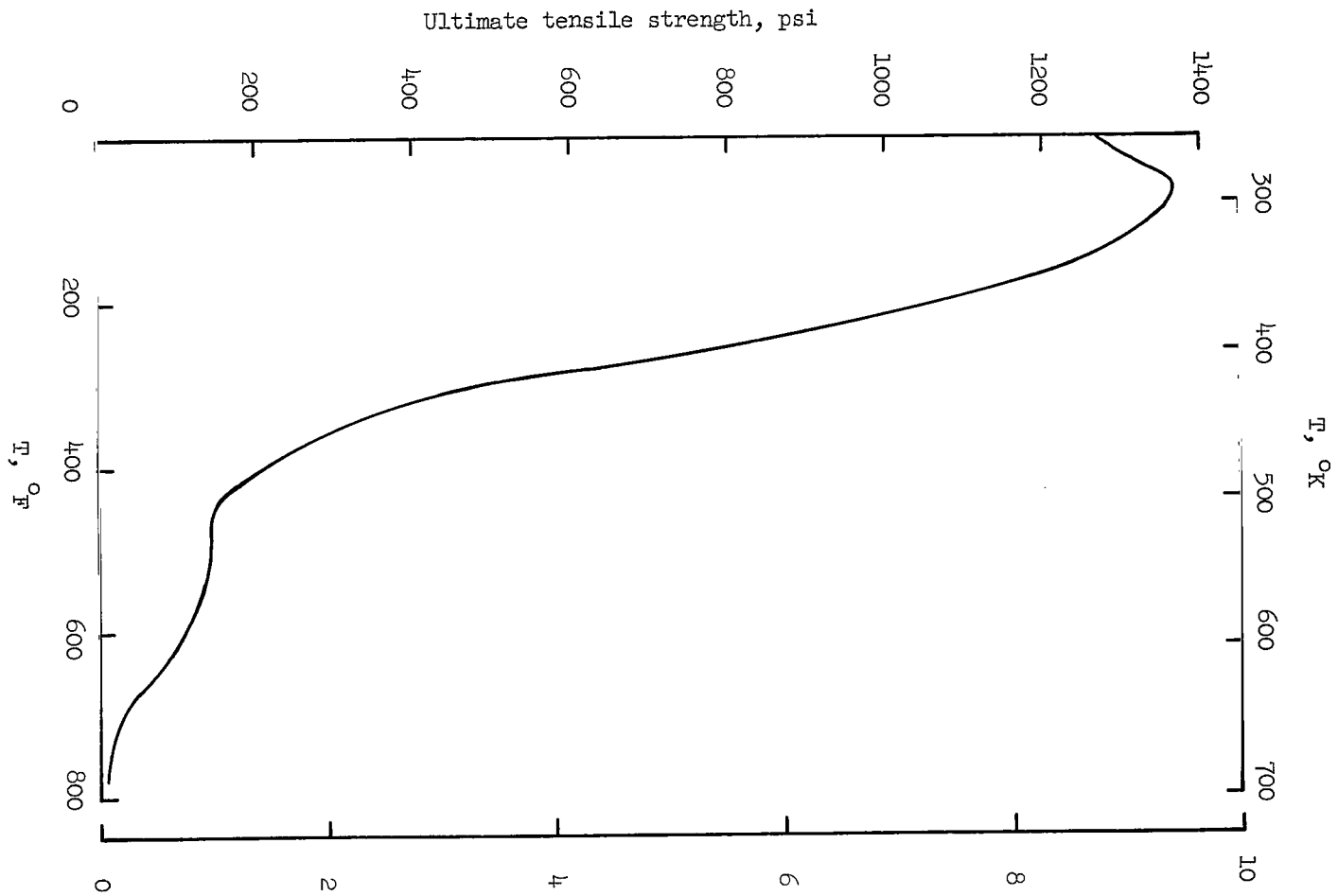


Figure 7.- Ultimate tensile strength of phenolic nylon.

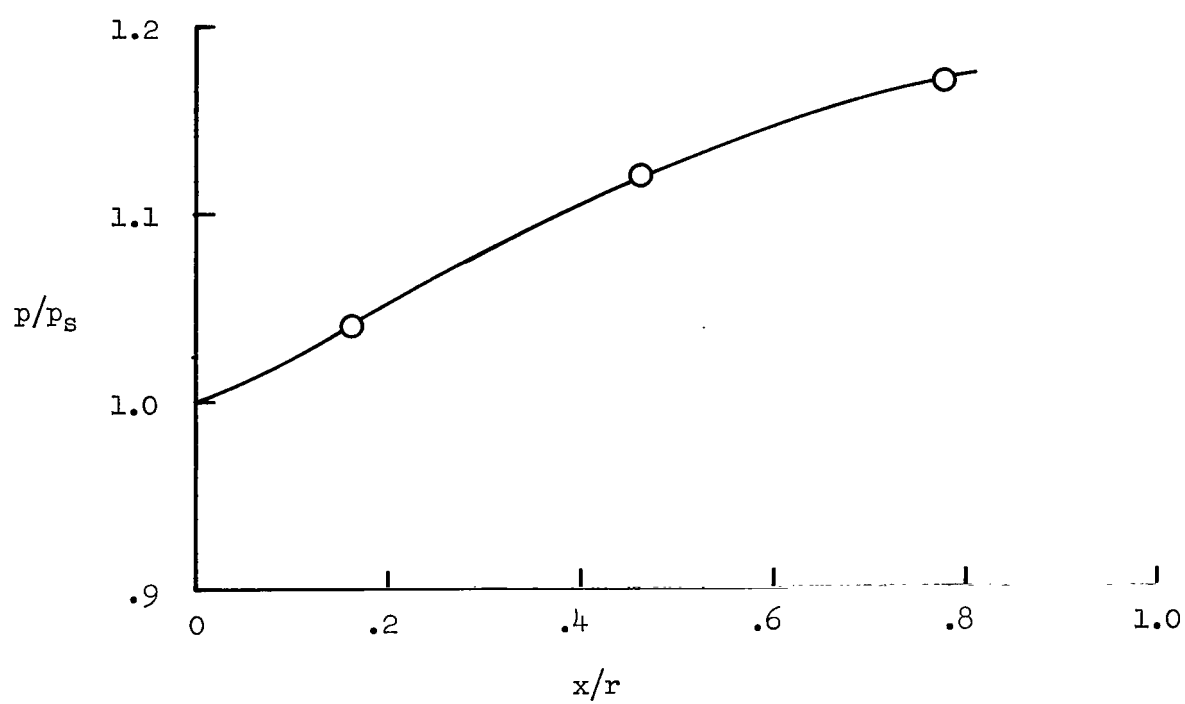


Figure 8.- Pressure distribution along surface of specimen in test condition 11.

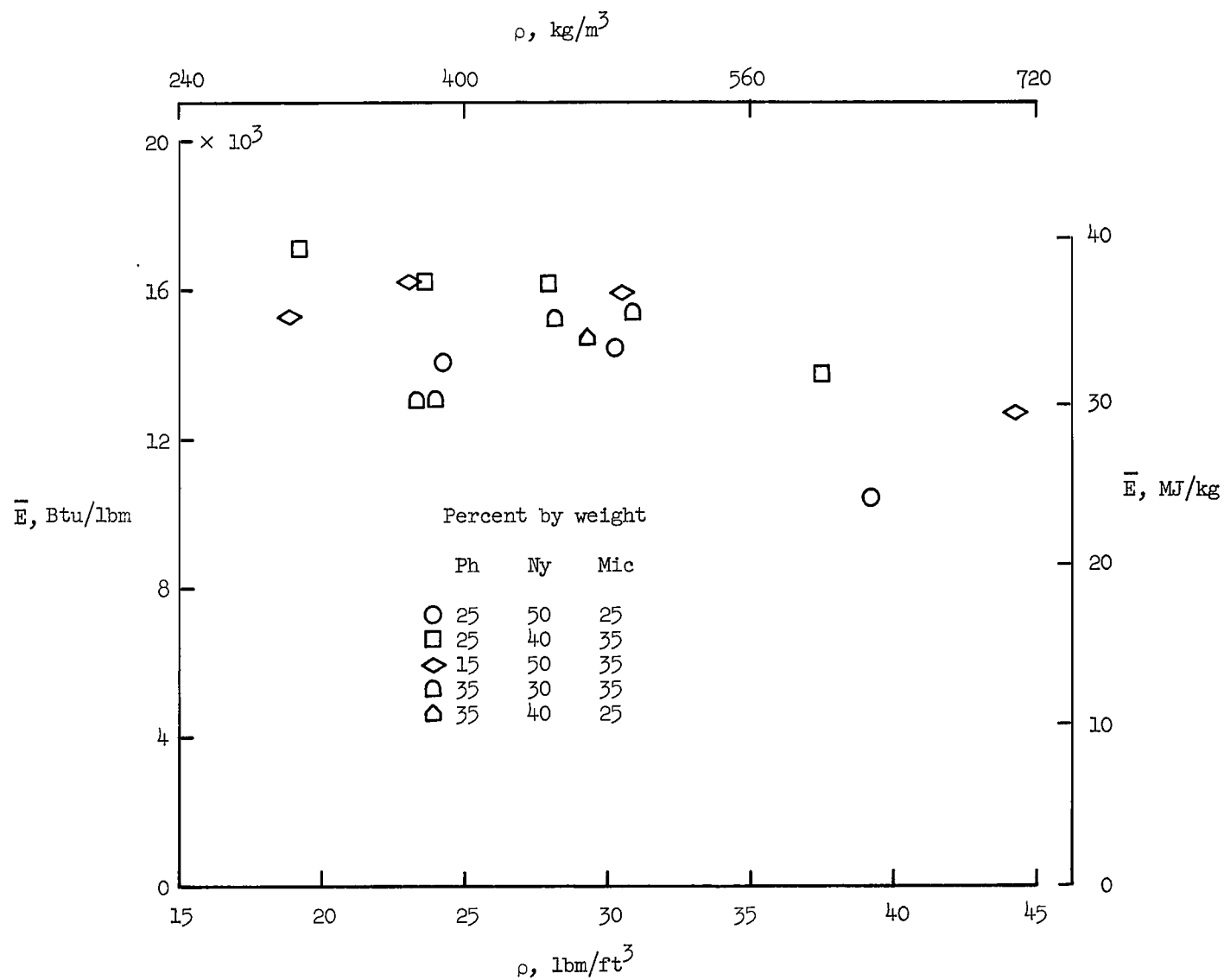
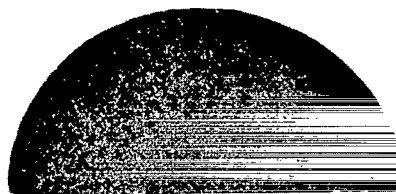


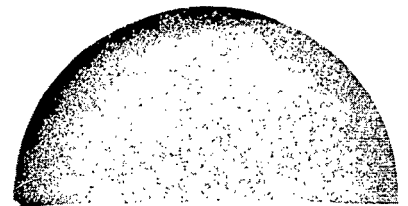
Figure 9.- Effect of density on effectiveness at test condition III.



$$\rho = 24.2 \text{ lbm/ft}^3 \\ (387 \text{ kg/m}^3)$$

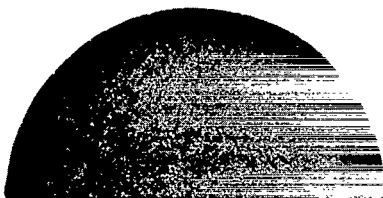


$$\rho = 30.3 \text{ lbm/ft}^3 \\ (485 \text{ kg/m}^3)$$

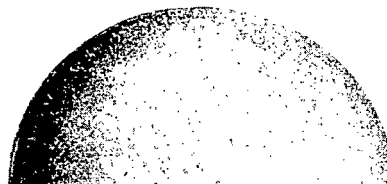


$$\rho = 39.2 \text{ lbm/ft}^3 \\ (627 \text{ kg/m}^3)$$

(a) 25 percent phenolic, 50 percent nylon, 25 percent Microballoons.



$$\rho = 24.1 \text{ lbm/ft}^3 \\ (386 \text{ kg/m}^3)$$



$$\rho = 27.9 \text{ lbm/ft}^3 \\ (446 \text{ kg/m}^3)$$



$$\rho = 37.5 \text{ lbm/ft}^3 \\ (600 \text{ kg/m}^3)$$

(b) 25 percent phenolic, 40 percent nylon, 35 percent Microballoons.

Figure 10.- Surface condition after testing in condition III.

L-66-7633

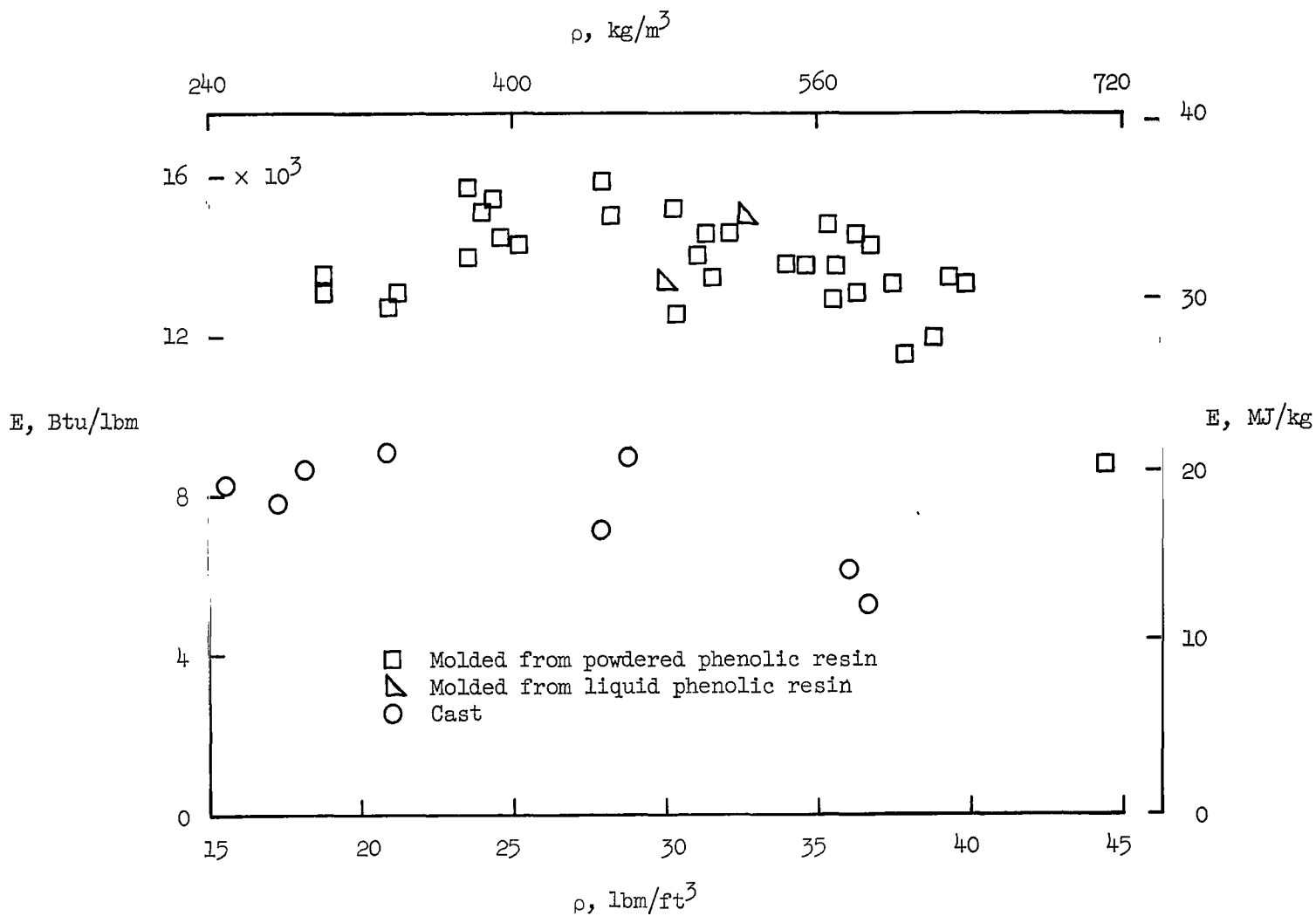


Figure 11.- Effectiveness of molded and cast phenolic nylon at test condition I.

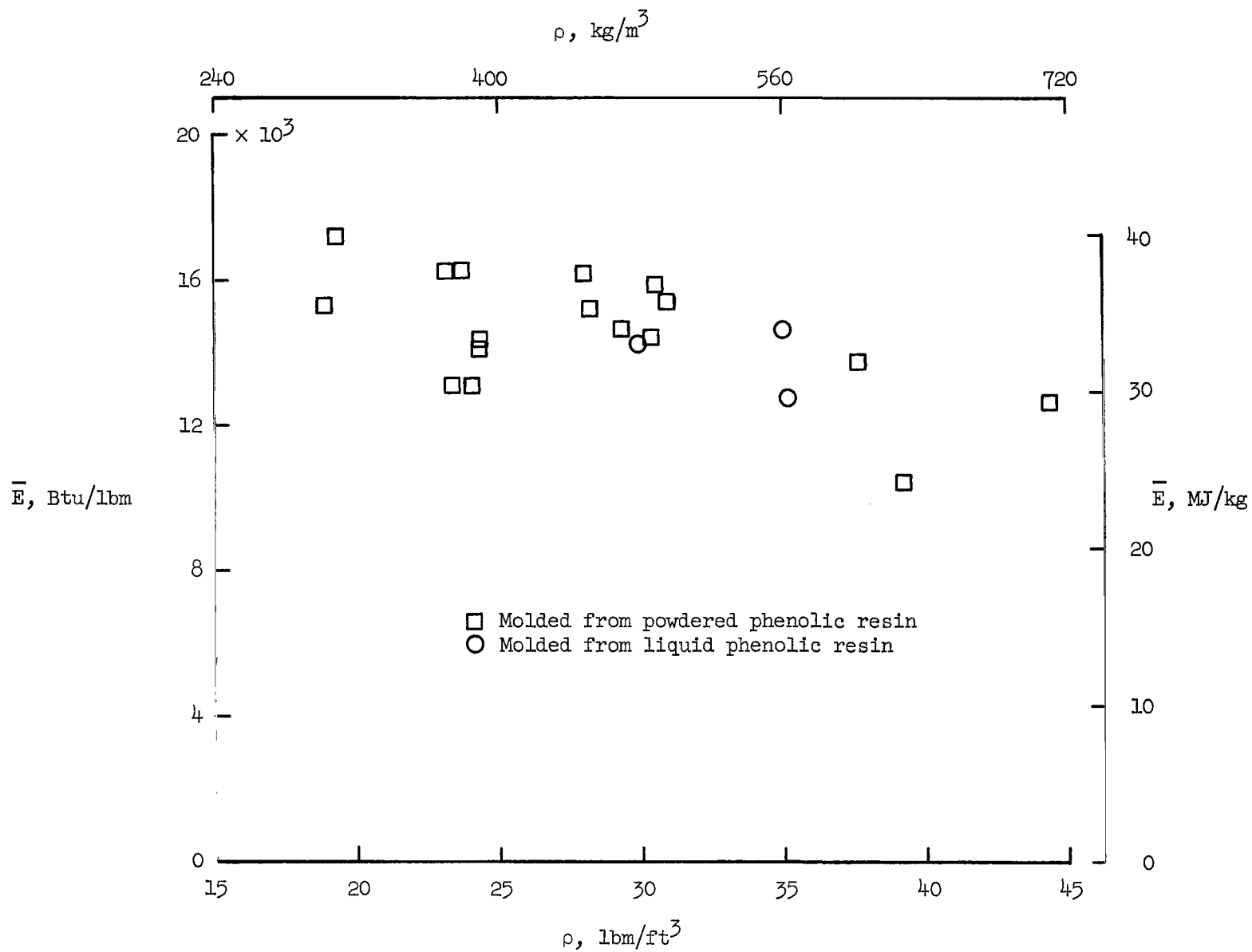


Figure 12.- Effect of phenolic resin on ablative performance at test condition III.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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